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V. *Cases of Colour-blindness, No. VI to No. XVIII, together with
Eleven Selected Examples of Normal Colour Sensations.**

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SINCE the publication of my paper on “Artificial Temporary Colour-blindness,”* I have examined the colour sensations of several hundred people, including a number of cases of colour-blindness, which I propose in the present communication to describe and to discuss.

I had two objects in view, namely, to obtain a sufficient number of measurements from persons of normal vision to serve as a fair standard of normal colour sensations, and also to obtain as many examples as possible of the different varieties of partial or complete colour-blindness.

Method.

The method employed is that described in my paper, with some modifications suggested by my experience with the colour-blind.

A spectroscope of wide dispersion must be used, so that not more than one-tenth part, at the most, of the spectrum can be seen at one time. The field of view must be wide, a Kellner eye-piece answering admirably, since flatness of field is not required, and sharp definition is of secondary importance. A good bold pointer in the centre of the field is far better than cross wires, which are difficult to see in the faint light at the ends of the spectrum. [It is essential that there should be no admixture of light from other parts of the spectrum reflected by the tubes, or of white light. Hence prisms answer better than a grating.—August 28, 1907.]

First Stage.

The first stage of the examination is as follows: the subject, having adjusted the illumination to that degree most pleasant to himself, is asked to examine the spectrum from end to end, and point out the parts where changes in the character of the light occur, naming the colours himself. The usual order is given below, the principal colours—i.e., those specified by the largest number of observers—being printed in capital letters, and those next in importance with initial capitals:—

deep-red, RED, scarlet, Orange, Yellow,
yellow-green, GREEN, Blue-green, BLUE,
indigo, VIOLET.

* N.B.—Cases No. I to No. V were published in my paper on “Artificial Temporary Colour-Blindness,” ‘Phil. Trans.,’ B, vol. 191, 1899, pp. 1–34.

† ‘Phil. Trans.,’ B, vol. 191, 1899, pp. 1–34.

Of the four principal colours, violet is the one about which there is most uncertainty. The name appears to be associated in the popular mind with purple rather than the violet of the spectrum. One often hears the remark, "Real violet has more red in it." In point of fact, the flowers and paints and dyes called "violet" invariably give a spectrum containing red rays. But this colour, whatever be the name given to it, is recognised by the majority as one of the principal colours of the spectrum.

Minute care in giving names to all the gradations of tint between red and green, or even throughout the entire spectrum, is no proof that the colour sensations are normal. I have known a man give NEWTON'S seven colours quite correctly, and five minutes afterwards, when shown the F-line under a much higher power, call it "pink." One of EDRIDGE-GREEN'S tests—and it is a very effective one—for colour-blindness, is founded on the fact that lowering the illumination will often completely throw a man out if he does not really possess the sensations necessary to discriminate between two colours.

One or other of the following indications of abnormal colour sensations may be obtained during this part of the examination :—

Spectrum shortened at the red end.

No colour-change at D.

A strong colour-change at *b*.

A band of grey, pink, purple, or nondescript colour between *b* and F.

No colour-change at G.

Spectrum shortened at the violet end.

Second Stage.

The next stage of the examination in the case of normal vision is very simple. The subject is asked to select the part which he considers the purest yellow—or, failing that, the colour midway between red and green—then, after having looked steadily at red between B and C for 30 seconds, he is to find this selected colour as quickly as possible.

If, as YOUNG taught, this neutral yellow results when red and green are equally excited, then the lessening of the red sensation by fatigue will cause it to be balanced by a smaller amount of green, and the neutral yellow will be found nearer the red than before.

Similarly, after 30 seconds' fatigue by green light between E and *b*, the green-blue junction will be found nearer the green.

And after 30 seconds' fatigue by blue light just beyond F, the blue-violet junction, normally at G, will shift nearer to F.

I usually take all four colours in succession thus, in order that the subject may forget the exact position of the colours before he comes back to them the second

time, and for the same reason, I use the widest dispersion at my command. I next ask him to trace the visible spectrum to its extreme limit in the violet, and when this has been done, fatigue the eye for 30 seconds with violet near H, and ask him to find the beginning of blue. This should be, for normal sight, well to the violet side of G. Similarly, after 30 seconds' exposure to blue, he finds the green extending beyond F.

The test is completed by 30 seconds' fatigue with green, when the red should be found between E and D, and should be traced as far as B or A, according as diffused daylight, or direct sunlight or the electric arc, is used. By suitably plotting the results so obtained, the relative strength of the colour sensations is shown.

The Method in Cases of Colour-blindness.

The procedure is less simple in the case of the colour-blind, for they not merely use a different language, but have different sensations to express. Hence the importance of a test that eliminates all questions of nomenclature and judgments of the mind, and depends only upon the most elementary of all perceptions, namely, the *consciousness of a difference*.

It is not necessary even to know the names given by the subject to the colours. I generally say, in the first stage of the examination, "Turn the screw till you come to a part that looks different, and bring that part up to the pointer." Now, such a difference may be either a difference of intensity, or a difference of quality, that is to say, of colour sensation. The first stage of the examination does not decide between these alternatives, but the second discriminates between them in a very remarkable and instructive way.

For example, a person with normal colour sensations describes the spectrum as red up to C, then changing gradually through orange to yellow a little beyond D, and so passing into green, which extends to F, or thereabouts, where the next striking change occurs.

A green-blind person may, in the first stage of the examination, describe "yellow" as beginning at B, and extending to *b*, where the most striking change is found, so that we might be led to suppose that he has a yellow sensation in place of green.

The second stage reveals a fundamental difference between the two cases in their reaction to fatigue.

The *normal eye*, after exposure to red light, finds the yellow *nearer the red end of the spectrum*.

The *green-blind eye*, after exposure to red light, finds the "yellow" *farther from the red end of the spectrum*, because the so-called "yellow" is merely the brighter part of the red sensation, the "difference" perceived being one of quantity, not quality, so that, when the eye is fatigued for red, this "difference" is not found so near the end of the spectrum as when the eye was fresh.

I drew attention to the corresponding phenomenon in the blue and violet in my previous paper, but did not then realise its importance in practical testing.

Part of the difficulty in applying the test to cases of colour-blindness is due to the fact that their deficiencies as regards colour are frequently compensated for by an abnormally keen perception of intensity, and they accordingly notify three or four additional points of change, each of which has to be tested. And moreover, until some idea has been formed as to the relative extent of their existing colour sensations, it is impossible to decide on the proper wave-length for producing fatigue.

Typical Examples of Normal Colour Sensations.

In my previous paper,* I have given the average limits in wave-lengths of the colour sensations of 70 persons who might be considered normal in the sense that none of them were colour-blind.

They were, however, not all alike, for 24 out of the 70 could see beyond K, and remarked on the peculiar brilliancy of the violet.†

Obviously, in setting up a standard of colour sensation, a selection of the most perfect examples should be taken, rather than the average between the very good and the mediocre. I have accordingly taken 10 of the best—that is to say, of those who could see beyond A in the red and beyond K in the violet—who passed the most severe tests with HOLMGREN'S wools, and who had no difficulty in locating the change of hue in the spectrum where blue passes into violet. They were all tested by the method of fatigue for 30 seconds with light of moderate intensity, such as is used in ordinary work with the spectroscope.

To these I have added one who is interesting as being the brother of the two cases of red-blindness specially described in my previous paper. His colour sensations were quite normal, and he could see K, but not the iron lines beyond K in the arc spectrum which were visible to all the others.

Evidence of a Separate Sensation for Blue.

It will be observed that I have definitely included Blue among the normal colour sensations. Since 1899 I have examined several hundred persons whose colour sensations were normal, and I find that what I then said about the existence of a blue colour sensation, as distinct from violet, is confirmed. In view of the fact that this statement brings me in conflict with the accepted forms of YOUNG'S theory and also with that of HERING, some discussion of the evidence may be permitted.

The conclusion drawn from my experiments, that no one colour sensation is related to any other in the sense indicated by HERING, receives collateral confirmation from the observations of WALLER on the retinal currents of the frog's eye excited by

* 'Phil. Trans.,' B, vol. 191, 1899, pp. 21 and 25.

† Ditto, p. 24, bottom.

light.* “Coloured lights act in the same direction, and in accordance with their luminosity. No electrical evidence is obtained of antagonistic influence.”

Again, the measurements by GOTCH† of the time relations and E.M.F. of the retinal response to light from various parts of the spectrum strongly support YOUNG’s fundamental conception of separate independent colour sensations. He found three varieties of response—that to red light, characterised by long latency and moderate E.M.F., that to green light by very short latency and greater E.M.F., whereas the response to violet showed moderate latency and small E.M.F. Moreover, “it was found that on either side of the green region the response always tended to resemble in its time relations that evoked by green light.” In so far, therefore, as my observations are antagonistic to HERING’s theory, these experiments on the response of the frog’s retina may fairly be held to confirm them.

But as regards the point on which I differ from the YOUNG-HELMHOLTZ theory, they afford me no support. Yet I think they do not contradict my view, and for two reasons. One is that the spectrum of the arc is rich in violet and green and relatively poor in that part of the blue by which the sensation, if it exists, should be excited, so that, as GOTCH says: “the negative character of the results at present obtained cannot be regarded as conclusive.” The other reason is that this sensation in human beings is so variable as to its intensity and extent that in a quite considerable percentage of cases it is difficult to discriminate between it and violet. But on the other hand, to those who possess both, there is just as striking a difference between blue and violet as there is between red and green. It is not a little remarkable that in an animal so far removed from the human being, experimental evidence should be found of three kinds of specialised response to light, and it might well be that a fourth, present in most of us, is absent in the frog.‡

The positive evidence in favour of the existence of a separate colour sensation for blue, resulting from my measurements of colour sensations during the last 10 years, is as follows:—

1. To the majority of people there are three regions of the spectrum where the change of colour is more rapid than elsewhere, namely, in the neighbourhood of D, F, and G.
2. At D the change is from red to green through yellow, and to about three people out of ten it is gradual and spread over a considerable distance, so that the exact

* ‘Phil. Trans.,’ B, vol. 193, 1899, p. 162.

† ‘Journal of Physiology,’ vol. 31, p. 28, 1904.

‡ HANS PIPER, ‘Archiv für Anatomie und Physiologie,’ Physiologische Abtheilung, Suppl., 1905, p. 172, finds that for night-birds the maximum excitation of the retina is given by light of λ 5350, which corresponds well with the maximum of the green sensation in man. For day-birds he gets maximum excitation with λ 6000. My observations give about λ 6368 as the maximum of the red sensation in man.

point of change is difficult to locate, and yellow is one of the important colours of the spectrum, the rest regarding it as unimportant and a mere transition colour between green and red.

3. At F the change is from green to blue through blue-green, which the great majority recognise as a mixed colour, though it evidently, in the eyes of a minority, more nearly agrees with their idea of pure green than the region about *b* where the green sensation is most strongly excited.

4. At G the change is from blue to violet through indigo, and to quite a number of people the change of hue is spread over so large a space that they find a difficulty in pointing out where it begins or ends, exactly as some other people find a difficulty in locating the yellow.

5. After fatigue by blue the violet appears to reach farther into the blue, and at the same time the green appears to reach farther into the blue, just as after fatigue by green the blue appears to reach farther into the green on one side and the red does so on the other.

6. If violet were merely a darker shade of blue, as three or four people out of ten say when questioned closely, then after blue, violet should reach farther into the blue and, in addition, after violet the violet should reach farther into the blue. This *I have frequently found to be the case, but only with those who have a difficulty in locating the change of hue near G.* Several instances of it will be found among the cases of colour-blindness described in this paper. It may indicate either a weak blue or a weak violet. In all cases of normal sight, fatigue by violet causes the blue to reach farther into the violet.

7. If blue were violet mixed with green, then on fatiguing for green the blue-violet junction should move nearer blue, but it does not in any of the cases I have tested.

8. If violet were blue mixed with red, then on fatiguing for red the blue-violet junction should move, the blue extending farther into the violet, which should be diminished. But no amount of fatigue of the red has the slightest effect on the violet, either in my own case or in any that I have tried.

For these reasons I consider blue and violet to be independent colour sensations.

I have applied the same tests to yellow with the greatest care in a great many cases, but can get no evidence of its existence as a separate colour sensation. For instance, I cannot fatigue yellow without also fatiguing green. If, by exposure to yellow, I bring the red-yellow junction nearer the yellow, I find that at the same time the green-blue junction has moved nearer the green.

I conclude, therefore, that yellow is not a separate colour sensation.

"Yellow" seems to be the name given by the green-blind to the red sensation and by the red-blind to the green sensation.

The tables (p. 237) show that there may be considerable differences in the spectral extent of the various colour sensations between individuals, and I have reason to know

that they vary in the same individual according to what he has been doing, and also, I am inclined to think, according to his state of health.

TABLE showing the Extent of the Colour Sensations in Eleven Cases of Normal Vision.

(The wave-lengths are expressed in Angström units.)

	Red.	Green.	Blue.	Violet.
E.	A 5665	6060 4775	4985 4280	4470 K
S. P.	A 5720	5910 4760	5040 4410	4615 K
M. H. D.	A 5565	5960 4750	5110 4330	4600 K
K. H. D.	A 5460	6040 4800	5130 4270	4550 K
G. M.	A 5560	5965 4500	5270 4230	4730 K
A. R. W.	A 5590	6050 4820	5220 4230	4730 K
E. C. A. W.	A 5630	6230 4780	5210 4210	4520 K
R. B. G.	A 5760	6370 4740	5170 4410	4635 K
I. C. B.	A 5550	6010 4720	5080 4555	4740 K
G. J. B.	A 5360	6200 4735	5210 4570	4620 K
S.	A 5790	6070 4815	5190 4380	4750 K

TABLE showing the Mean Positions of the Junctions of the Colour Sensations, and the Amount of Overlap.

	Red-Green.		Green-Blue.		Blue-Violet.	
	Junction.	Overlap.	Junction.	Overlap.	Junction.	Overlap.
E.	5863	395	4880	105	4375	190
S. P.	5815	190	4900	280	4513	205
M. H. D.	5763	395	4930	360	4465	270
K. H. D.	5750	580	4965	330	4410	280
G. M.	5763	405	4885	770	4480	500
A. R. W.	5820	460	5020	400	4480	500
E. C. A. W.	5930	600	4995	430	4365	310
R. B. G.	6065	610	4955	430	4523	225
I. C. B.	5780	460	4900	360	4648	185
G. J. B.	5780	840	4973	475	4595	50
S.	5930	280	5003	375	4565	370
Average	5842		4946		4493	

My own case, quoted under my initials, is a good example. Usually my blue-violet overlap is very large—on this occasion it was only 50 Ångström units. On the other hand, my red-green overlap was greater than that of any of the others.

Probably it was due to my having had to focus the spectroscope and adjust the light for others before I tested myself, and the effect of fatigue on the blue and violet is so much more persistent than on the red. But it will be observed that

although the extent of the overlap is so greatly reduced, the position of it is not much altered, though it undoubtedly shows somewhat greater fatigue for violet than for blue.

CASES OF COLOUR-BLINDNESS.

Preliminary Observations.

Three points are brought out strongly by a comparison of the following cases of colour-blindness :—

1. There seem to be a good many different varieties of colour-blindness. Theoretically, if there are four independent colour sensations, the total number of possible cases is 15, viz.—

**Normal,	possessing	.	.	.	.	Red, Green, Blue, Violet.
**Lacking one,	„	.	.	.	.	Green, blue, violet.
**	„	.	.	.	.	Red, blue, violet.
*	„	.	.	.	.	Red, green, violet.
**	„	.	.	.	.	Red, green, blue.
Lacking two,	possessing	.	.	.	.	Blue, violet.
„	„	.	.	.	.	Green, violet.
*	„	.	.	.	.	Green, blue.
*	„	.	.	.	.	Red, violet.
*	„	.	.	.	.	Red, blue.
„	„	.	.	.	.	Red, green.
Lacking three,	possessing	.	.	.	.	Red.
*	.	.	.	.	.	Green.
*	.	.	.	.	.	Blue.
.	.	.	.	.	.	Violet.

I have met with complete cases of those marked with two asterisks and partial cases of those marked with one.

2. It is very seldom that any one colour sensation is totally deficient. A careful examination will in most cases, though not in all, reveal traces of the sensation in the proper part of the spectrum.

3. There seems to be a species of compensation by which, if one colour sensation is absent, the relative sensitiveness of one near it in the spectrum may be increased. Only in one case have I found any gap in the spectrum, or region of diminished luminosity.* Amongst the cases described in this paper there are at least two who may be regarded either as having one colour sensation abnormally strong, or three colour sensations unusually weak. It would almost seem that for the complete characterisation of the colour sensations in some cases, one should specify not only those sensations which are lacking or below the normal, but also those which

* This will be described in a future paper.

transcend it. It is, in fact, possible to be colour-blind, though having one colour sensation stronger than it should be. No. XVII is a case in point.

For convenience of reference, I propose to assign a number to each case of colour-blindness described by me. Nos. I to V will be found in my previous paper.*

No. VI.—*Red-blindness.*

This was a patient from the Oxford Eye Hospital, where he had been tested with HOLMGREN'S wools. A young man about 20 years old. Had been apprenticed to a coach-painter, but was found utterly incapable of mixing his paint correctly. His difficulty seemed to be partly one of education. Not being able to see colours as they appear to the normal sighted, he had never learned how to interpret the sensations he possessed, and his vocabulary was limited and uncertain. His examination with the spectroscope was a matter of some difficulty on this account.

Unfortunately, the spectroscope had, unknown to me, been taken to pieces for cleaning and the prisms moved so that the calibration curve was altered. I am therefore unable in this case to give wave-lengths.

He described the colour of the spectrum at D as "yellow,"† changing to a "darker yellow" in the neighbourhood of C, and ending a little beyond that point.

In the other direction it was "yellow" as far as *b*, where it changed to a "bluish-white," which about half way between *b* and F gave place to "blue."

"Blue" changed to "darker blue" a little before G, and this continued to the end of the violet. He saw the calcium lines λ 3967 and λ 3983 easily, and therefore has the violet sensation.

With regard to blue, he placed the junction of "blue" with "darker blue" at 903 scale before fatigue. After fatigue with blue, he found it at 870 scale, *i.e.*, nearer the blue, and after fatigue with violet, he found it at 975 scale, the reaction being in both cases *towards* the colour used as stimulus. This proves him to have the normal reactions for blue on the violet side.

After fatigue by blue, he found "yellow" extending well beyond F, and after fatigue by green, he found "blue" about half way between F and *b*, and "bluish-white" extending from that point to *b*, so that he has the normal reactions for blue on the green side also.

His "yellow" is obviously our green. He has no red, or so little as to be unrecognisable. His "blue" is our blue, and is normal; so is his violet sensation, which he names "darker blue." His "bluish-white" is analogous to the orange of the normal sighted, for orange is where the second colour sensation, green, begins to make itself felt under the first, red. He has no red, but where his first colour sensation, green, which he calls "yellow," begins to be modified by his second colour sensation, blue,

* 'Phil. Trans.,' B, vol. 191, 1899, pp. 1-34.

† N.B.—Names used by the colour-blind themselves are distinguished by inverted commas.

which he calls by its right name, he is conscious of a difference, to which he gives the name of "bluish-white."

No. VII.—*Red-blindness.*

A Classical Lecturer.

So far as I know, he was not familiar with spectroscopes, and had no preconceived ideas of the order in which the colours should come.

I began as usual with the red. This he called "green," or "a colour he could not name," and said it changed to "yellow" near C. He described the change in colour as very slight, and was very uncertain about it. After working in the region of *b*, he placed the junction of "green" with "yellow" close to the sodium lines. This would indicate that his "green" may be a very faint trace of the red sensation, too weak to do more than slightly modify the tone of the green sensation which he called "yellow." To complete the proof, the effect of fatigue by what he called "green" should have been tried, but his eyes became tired before we reached that point.

He found a very noticeable change from "yellow" to "blue-green" about *b*, which is where blue begins underneath the green. This answers exactly to the "bluish-white" of the previous case (No. VI), and as has already been pointed out, this change, to a person without the red sensation, would correspond to the change from pure red to orange of normal sight.

After fatigue with blue, this change of hue shifted towards the blue in a quite normal way.

He found another change from "bluey-green" to "blue" a little beyond F, the usual position with persons who have the green sensation strong. After fatigue with blue, this change of tint also moved farther into the blue.

In the neighbourhood of G he found another change from "blue" to "dark-blue," but he seemed very uncertain about it. With daylight he thought it "merely a difference in intensity," being, I fancy, misled by the dark lines near G, but with the arc-light he said the colour was different. The bright lines of calcium (H and K) were visible to him.

His eyes were easily tired with the light, so that I was not able to continue the examination long enough to get at the complete explanation of his nomenclature of certain colours.

His blue-green junction was quite normal as to the effect on it of physiological fatigue, and as to position, it indicated a *strong* green sensation. His spectrum was shortened at the red end, but not so much as in the case of the totally red-blind—it reached, in fact, farther than I could trace my own green sensation during artificial red-blindness.

For this reason I think he must possess some traces of a red sensation, and also because of the curious uncertainty he manifested concerning this part of the spectrum.

Our green he ordinarily called "yellow." What looked red to me was always either "green" or "a colour I cannot name" to him; but the *same colour was sometimes called by one name and sometimes by the other* after a few minutes' interval, if he did not know it to be the same. Red objects did not strike him as bright coloured, but rather dark. He generally spoke of them as "green," but with something about the colour that puzzled him. He never showed any hesitation about colours of shorter wavelength than D.

All this confirms the supposition that he was nearly, but not quite, red-blind. He had a strong green sensation, and undoubtedly possessed the violet sensation. Probably a completion of the fatigue experiments would have shown the blue-violet junction to be normal, as the reactions for blue were certainly normal on the green side.

No. VIII.—*Partial Red-blindness with Strong Blue.*

Had failed to pass the test at Sandhurst. Could recognise bright colours, but was not successful with the confusion tests.

On the one hand, he was unable to trace the spectrum quite as far as B, and even after fatigue with green, he placed the "red-green" junction on the red side of the D lines.

When not fatigued, he found "red" change to "green" midway between D and C.

The "blue-green" junction he placed about midway between *b* and F. After fatigue by green, he made "blue" begin at *b*, and, after fatigue by blue, his "green" sensation extended a little beyond F, but rather less than more than the average.

His "blue-violet" junction was well marked—rather farther towards the violet than the average, but quite normally affected by the fatigue tests. He was able to trace the spectrum nearly up to H by diffused daylight.

It will be observed that he called all the spectral colours by their correct names.

From the foregoing, I conclude that his violet sensation is normal, few people being able to see up to H save by the direct light of the sun.

His blue sensation is rather stronger than the average. This is shown both by the position of the junction with violet, and by his tracing the blue as far as the *b* lines.

His green is normal, for it does not reach so far into the blue as the average, and the reason why it extends so far into the red is that the red is deficient.

He may therefore be regarded as partially red-blind, with compensation in the blue.

No. IX.—*Probably Partial Green-blindness.*

An Evening Student at Science Classes.

This case was brought to me when I was away from home. Only a single-prism spectroscope being available, I was not able to apply the fatigue tests.

According to his description, the spectrum began with "orange-red," which became gradually brighter, especially about λ 5800, which he described as "a lighter shade of the same colour."

The most distinct change was from "reddish-yellow" to "dark purple" at λ 5070. Farther on this passed into "bluey-purple," which gradually became darker until it faded away into black.

I subsequently fixed a small reading telescope, magnifying five times in the optic axis, in series with the telescope of the spectroscope. This arrangement increased the magnifying power five-fold, and reduced the light considerably, so that he completely lost count of what the colours ought to be. He accordingly called red "reddish-yellow," which he said got brighter and brighter, without any change of colour that he could identify, until the point above referred to, when it suddenly became "pink." Green he called "yellow," and blue "pink."

I came to the conclusion that he possessed a weak green sensation and a strong blue sensation. I could not test for violet, for lack of proper light. Probably the reason why he spoke of spectral red as "orange-red" or "reddish-yellow" was that, being nearly green-blind, oranges would be to him the same colour as vermilion is to us, and that his idea of red was derived mainly from red flowers, many of which contain blue, to which he was very sensitive.

No. X.—*Probably Partial Green-blindness.*

An Evening Student at Science Classes.

This case was brought to me on the same evening as No. IX and tested with the same spectroscope.

Both he and the previous case confused reds and greens, and pink appeared a dirty colour to them, what No. IX called "pink" being in reality a greenish blue. In neither case did the spectrum seem shortened in the red.

According to No. X, the spectrum changed to "yellow" at λ 6700. It became "full yellow" at λ 5500, and was "pure blue" at λ 5070, there being a transition colour that he could not easily describe between "yellow" and "blue" from λ 5335 to λ 5070. After λ 5070 there was no farther change of tint.

Farther tests of both this and the previous case are much to be desired, but both struck me as cases of partial green-blindness.

No. XI.—*Partially Green-blind, with Strong Blue Sensation.*

An Undergraduate, not Scientific, brought to me by one of the Physiological Students.

Confused pale pinks and greens, and also pale tints of mauve and azure blue with pale tints of green and brown.

His description of the spectrum was interesting, because he called the same part of it by different names on its being shown him a second time.

According to him, the spectrum began with "orange," passing to "yellow" at about C. "Yellow" changed to "green" near D, and then passed through "some other colour" to "mauve" or "pink" close to the *b* lines.

A few minutes later, not knowing he was being shown the same thing, he said the "indefinable colour" passed into a "watery blue."

On another day, the part he had previously said was "indefinable" he pronounced "muddy green"—the "watery blue" he now called "pink," and the part he had described as "yellow" he called "green."

The fatigue tests showed him to have all four colour sensations, but not of the same relative intensity as most people. The change from red to green was much less noticeable to him than that occurring where most people see none, viz., near the *b* line. This was evidently the overlap of his blue and red sensations. It was affected by fatigue in a quite normal manner, as was also the boundary between blue and violet. But he had some difficulty in making observations on the overlap of green and red, and on the overlap of green and blue, both of which seemed ill defined to him.

Owing to the confusion of terms used by him in describing these colours, I was not able to complete the fatigue tests in regard to them before it was necessary for him to leave.

So far as I could make out, his "red" is the faint part of the pure spectral red, and his "orange" and "yellow" the brighter and brightest parts of it. His "green" occurs where we see yellowish green, and his "indefinable colour" or "some other colour" being in the place of pure green. His "mauve" or "pink" is our blue-green, his "greeny blue" is our blue, and his "true blue" is our violet.

Judging by my own experience during partial artificial green-blindness, I should say that his mental impression of the colour he calls "green" is that of a pale yellow-brown, like yellow ochre mixed with white, or a yellow leaf in autumn.

He has the blue sensation strong, the violet about normal, the green very weak, and the red perhaps slightly so.

No. XII.—*Partially Green-blind, with very Strong Blue Sensation.*

A Physiologist, fully aware of his peculiarity and desirous of investigating it by my method.

With HOLMGREN's wools, he confused together greens, greys, and bronze-browns.

He gave the following names to the colours of the spectrum :—

"Red," changing to "yellow" at λ 5910, then "green" with a well-marked change at λ 5170 which he called "grey." At λ 4955 there was another though less definite change, to which he gave the name of "purply." Beyond this came "blue," and

finally between $\lambda 4120$ and $\lambda 4100$ there was a vague but unmistakeable change to "blue with crimson."

The interesting point about this case was that he saw all the colour-changes of the normal sighted, and in addition, one that is peculiar to the green-blind, namely that at b ; but his idea of the *relative importance of these colour-changes was abnormal*.

Thus, he considered the change to yellow at $\lambda 5910$ quite unimportant, but that at b , which he called "grey," and which is situated in what to most people is the very middle of the green where there is no change, was to him very strongly marked. His idea of "green" was associated with that part of the spectrum which we call yellowish-green, and the colour that he called "purply" corresponds with the blue-green of normal vision. But it must not be forgotten that he uses the word "green" in a totally different sense from that in which it is employed by the normal sighted. To him it means that the sum of the sensations excited by this part of the spectrum equals the sum of the sensations excited by the leaves of plants. Now in the spectrum of chlorophyll there is red to a notable extent, but blue and violet are deficient. In the spectrum, as he sees it, with the green sensation greatly reduced, there is, beyond b , excess of blue. This part, therefore, cannot represent green plants, because he misses the red in them. To the normal sighted the green predominates to such an extent in the neighbourhood of b , and in the colour of the grass, that the blue on the one side and the red on the other, underlying the green, are quite unnoticeable until some distance on either side of b .

And I found during my own experiments on artificial green-blindness that green leaves appeared to me very much the colour of the part of the spectrum he called "green," not as I see it now, but as I saw it *during green-blindness*.

The colour that he called "purply" seems to correspond with the blue-green of normal vision. He described a skein of wool of a purple shade of grey as being "the colour of ivy leaves a little dusty."

His colour "blue with crimson" was obviously our violet, but not reaching so far into the blue as is usually the case.

His red-green junction varied very little after fatigue with red, and only moderately after fatigue with green. This generally indicates a weak green sensation.

To the normal eye, except under artificial colour-blindness, there is seldom any change at all at $\lambda 5170$, where he found the most striking change. The effect of fatigue by red light was to shift this colour-change to $\lambda 5350$, while, after exposure to blue light, he found it at $\lambda 5010$. Bearing in mind that I used much stronger light for fatiguing my own eye,* these numbers agree very well with those obtained by myself while artificially green-blind.

Undoubtedly his "grey" was the overlap of red with blue, which to ordinary persons is completely masked by the green sensation.

His green-blue junction was affected in the ordinary way by fatigue, but it was not

* 'Phil. Trans.,' B, vol. 191, p. 13.

at all well marked—agreeing in this respect with my own experience during partial artificial green-blindness.

His blue-violet junction was so ill defined that I could not get reliable measurements of the influence of fatigue, but he undoubtedly has the violet sensation.

The red lines of potassium were easily seen by him.

Conclusions.—He possesses a strong red colour sensation and very strong blue, with very weak green, and violet of perhaps normal intensity, the unusual position of the blue-violet junction being due to the extra strength of the blue sensation.

No. XIII.—*Red and Blue Strong, Green and Violet Weak.*

A Man of Culture. Not specially Scientific.

When tested with HOLMGREN'S wools, he confused fawn colour with dove colour, pink with pale cerulean blue, lilac grey with green-grey, etc.

Using the Marlborough spectroscope, high eye-piece, arc-light, he gave the following description of the spectrum:—

“Red” changes to a “nondescript colour” a little past the lithium β -line, at λ 6000. This changes to “green” close to b at λ 5180, the “purest green” being at λ 4845 not far from F. “Green” changes to “blue” at λ 4830, but he was doubtful about this.

Some time later he repeated this description with the following results:—

The alteration of the appearance of the spectrum about λ 6000 is very vague and indefinite, and there is no marked change of colour until λ 5200—a little way past E—where “red” changes to “green.”

(It should be observed that this second time he omitted the “nondescript colour” and traced “red” right up to “green.” This illustrates one of the difficulties met with in examining cases of colour-blindness.)

On farther inquiry he repeated that there was no striking colour-change until λ 5200. “Green” changes to “blue” at λ 4830—exactly the same as before—and “blue” changes to “indigo”—his own name for it—at λ 4660, *i.e.*, some little distance short of the blue line of strontium.

He seemed in doubt as to what name to give to the colour between λ 5200 and λ 4830. He called it “green” if he thought it ought to be green, but after looking at violet light he said it was blue. Sometimes, when he did not know what to expect, he called it “pink,” and at other times “grey.”

He called the colour to the red side of E “yellow” when fatigued slightly for red, and the spectrum on the other side of E he called “green” when fatigued for blue.

Fatigue tests showed his “yellow” to be little more than a change in the intensity of the red, for after red he found “yellow” at λ 6250 and after green he found “yellow” at λ 6255. After red he put the “green-yellow” junction at λ 5295.

There was not enough of his green sensation to fatigue green without touching red. An attempt to do so only fatigued the red, which underlay the green, more than it did the green, but the green could be fatigued without affecting the blue. Thus, after green at *b*, his "blue" began at λ 4970, and after blue his "green" began at λ 4770.

Summary.—His first striking colour-change is where red meets blue, and his next where green ends to the normal person. He must, therefore, possess the green sensation, though only in a slight degree. I noticed in my own case during artificial partial green-blindness the same inability to determine the exact limits of "yellow," the changes of which, however, keep pace with those of the "green," as the effect wears off. He evidently has the red sensation very strong, but violet, though undoubtedly present, is relatively weak.

The case may, therefore, be regarded as one of strong red and strong blue with weak green and weak violet.

No. XIV.—*A Weak Green with Strong Violet.*

An Undergraduate, not Scientific.

He placed the "best yellow" at λ 5480. This is much farther into the green than usual, the average for the 11 cases of normal vision given in this paper being λ 5840 and that for the 70 persons described in my previous paper being λ 5730.

After "yellow" he said the next change of colour was to "pink" at λ 5185. This corresponds with the mean position of the overlap between blue and red, λ 5205, during artificial green-blindness.

After "pink" he said the colour changed to "blue" at λ 4970. The average for the blue-green junction among the 70 normal persons was λ 5005, and for the 11 selected normal cases it was λ 4946.

Beyond this he said "full blue" changed to "darker blue" at λ 4400. The average position of the blue-violet junction for the 11 selected cases being λ 4493, and there being several of them quite near λ 4400, there was a possibility that this "darker blue" might be the violet sensation. On the other hand, it might be merely the falling off of intensity in the blue. Accordingly, I fatigued his eye with blue of λ 4790. After this he found "darker blue" at λ 4600, and traced it to a little beyond K.

He could see H with the utmost ease. I now fatigued him with the colour he called "darker blue," i.e., violet, and he found "blue" at λ 4230, saying he had gone too far, having come upon it sooner than he expected. Upon a second trial he found "blue" at λ 4190. Now the mean between λ 4600 and λ 4190 is λ 4395, which is almost exactly where he placed the "blue"—"darker blue" junction when the eye was not fatigued.

Trusting merely to the names given to the changes of colour, one might well have

said that for this man there was no separate sensation of violet. But the fatigue reaction, which is a purely physiological test independent of language, shows that his "darker blue" was normal violet.*

After fatigue with blue, I asked him to find "pink" or "green." He missed it altogether the first time, going straight past the green into the beginning of the red. On the second and third attempts he stopped at λ 4900 and λ 4875, but seemed unsatisfied, saying he had stopped too soon. As λ 4840 is the average limit of the green for the 70 persons, and for the 11 selected cases there is not one beyond λ 4820, he was distinctly below the normal in the extent of his green sensation on this side, and greatly below the normal as regards the intensity of it.

His red sensation extended to a little beyond λ 7606. He could see FRAUNHOFER A easily.

His green sensation appears to be weak, and his violet sensation somewhat strong.

No. XV.—*Probably almost Blue-blind.*

A Man of Culture, but with no Special Knowledge of Spectroscopy.

This case was in some respects unusual. The spectrum was not shortened, and in fact, extended farther into the red beyond A and into the violet beyond K than with most normal-sighted persons. But his description of the colours of the spectrum was abnormal. It was as follows:—"There are two principal colour-changes, namely, from red to green (at λ 5905) and from green to blue (at λ 4810), of which the latter is the more definite." So far, both of these agree sufficiently well with the normal junction of red with green and the effective end of the green for him to pass as normal sighted. His peculiarities appeared in the more detailed description.

From A to B he called "red." Beyond B it began to be tinged with "yellow," becoming "full yellow" at λ 6130. The sodium lines he called a "gorgeous yellow," but could not detect any rapid change of tint on each side of them, though to the majority of people the change is more rapid here than in any other part of the spectrum.

At λ 5185 he said "yellow" changed to "green," and on being asked to place the pointer so that there should be "yellow" to the left and "green" to the right of it, he set it finally at λ 5035.

During artificial green-blindness, I found the mean position of the red-blue junction to be λ 5241 when the eye was fixed on the junction, and it was only by fatigue with blue that I brought the red as far as λ 5040. Obviously, therefore, must be regarded as the utmost limit of the red rather than the junction of red with blue. In other words, blue, if present, is weak.

A little short of the F line at λ 4910 he said green changed to "deep pink." At

* Compare No. XV, page 248, line 17.

λ 4830 he called the colour "a mangy blue," and he put the beginning of violet at λ 4370.

I tried to find out whether the position of this colour he called "pink" would be affected by fatigue. After the colour he called "green" he missed the "pink" altogether, coming immediately to "mangy blue." After light from E he found "pink" at λ 5145, and after light from D he found it at λ 5070. This indicates that one constituent of his "pink" is the green sensation, since the "pink" was most powerfully affected by the light which excites the green sensation most strongly.

After fatigue by blue from midway between F and G, he found "pink" at λ 4890, a trifling change compared with that effected by green light.

The possible significance of this is seen on examining the effect of fatigue on the junction of the colours he called "mangy blue" and "violet." Before the eye was fatigued he placed this junction at λ 4370. After fatigue by blue he found the "violet" at λ 4380, *i.e.*, a trifle nearer the blue, but after fatigue by violet he found "mangy blue" at λ 4400. That is to say, the extent of what he called "mangy blue" was *lessened* by fatigue with violet instead of being increased as it would be if it corresponded with the "blue" of those for whom blue and violet are separate sensations.*

It seems probable, therefore, that the blue sensation in his case is lacking or nearly so, and that his "pink" is a mixture of green and violet.

Assuming this to be the case, his description of the spectrum may be interpreted as follows:—

A to B, "red"	Red.
B to <i>b</i> , various shades of "yellow" . .	Red + Green.
<i>b</i> to near F, "green"	Green.
Beyond F, "pink"	Green + Violet.
λ 4830 to λ 4370, "mangy blue" . . .	Violet with trace of blue.
Beyond this "violet"	Violet.

As it is probable that the maximum of the violet sensation occurs somewhere about λ 4360—at least, it would seem so from the 11 selected cases of normal colour vision—the portion from λ 4830 to λ 4370 would be markedly less luminous unless it were occupied to some extent by traces of a blue sensation, not strong enough, perhaps, to give the fatigue reactions properly, but sufficient to destroy the purity of the tint, as the term used in connection with this part of the spectrum seemed to imply.

* Compare No. XIV, p. 246, bottom.

No. XVI.—*Violet-blind.*

A Man of Culture. Not Scientific.

He was not tried with HOLMGREN'S wools owing to lack of time, but was said by his family to confuse blues and violets. He was tested with the Marlborough spectroscope, high-power eye-piece, and arc-light.

His description of the spectrum was as follows :—

“Red” changes to “Green” at λ 5920,

“Green” changes to “Blue” at λ 5180,

“Blue” changes to Violet at λ 4470,

but the blue-violet change was very indefinite, and he called violet sometimes “a darker blue” and sometimes “purple” if taken unawares.

Fatigue for 30 seconds with different colours, using the same intensity and width of slit, gave the following results :—

After red, “green” was found at λ 6280.

After green, “blue” was found at λ 5230.

After blue, “violet” was found at λ 4460.

End of spectrum = λ 4160.

The spectrum being short in the violet, it was necessary to fatigue with the most refrangible rays he could see that were bright enough, viz., λ 4200.

After λ 4200 for 30 seconds he missed his so-called “blue-violet” junction altogether, passing on to λ 4920, i.e., the change from blue to green for normal persons.

On trying a second time he found a change, which he called “the end of purple,” at λ 4810. (Note that, in some of the 11 normal cases, green is met with at this point.) After blue midway between F and G, he found “green” at λ 4980. After green, he found “red” at λ 5690, and, as he was able to see the potassium line in the flame spectrum, his red must extend to λ 7680. His green-blue junction is not quite so far in the blue as usual, indicating either a rather weak green or a strong blue, but, as the red-green junction is normal, and, after fatigue of red, “green” is found at λ 6280, i.e., well towards C, it seems more probable that the blue is strong and the green normal.

The interesting point about this case is the shortening of the spectrum in the violet. He was absolutely unable to see the bright lines of calcium λ 3967 and λ 3933, although to myself they were intensely bright.

The visible spectrum for him seemed to end almost abruptly at λ 4160, for there were two groups of bright lines in the arc spectrum not far apart, and both of them equally bright, one of which he could see, but not the other, even when I brought it

on to the pointer, so that he knew exactly where to look. (I believe these to have been the iron lines λ 4175, 4174; and 4173, which he could see, and the group λ 4158, 4157, 4156, which he could not see. It will be noticed that this is almost exactly the point to which I was able to trace the blue sensation when I had rendered myself temporarily violet-blind.)

Moreover, the fatigue tests give the same indication. His "after blue, violet" = λ 4460 is not very far from his "blue-violet" junction without fatigue, viz., λ 4470, but his "after violet, blue" = λ 4810, is farther from the violet than the normal junction, indicating that we are dealing with a change of intensity rather than the overlap of another colour sensation.

I consider, therefore, that this case is one of violet blindness, with, perhaps, an extra strong blue.

No. XVII.—*Abnormally Strong Green.*

A Swiss Girl of about 18, studying Art. Found to have a difficulty in Matching Colours.

This was an interesting case, but I had only a short time to examine it in, and for instrumental reasons, was not able to get measurements in wave-lengths. She could not trace the spectrum nearly so far, either in the red or the violet, as I could, but the fatigue tests showed her to possess all four colour sensations. They were not, however, normal in relative extent. The arc-light was not available, and it was a very dull day, so that I was only able to use a low power, and to compare her impressions with my own, under identical conditions.

After fatigue by red, she found "green" much farther in the red than I did, well beyond the lithium β -line. This is, of course, within the known limits of green, but it would have required a much more powerful red light to make me red-blind enough to see it there.

On the other hand, fatigue by green brought her "blue" barely half way from F to *b*, whereas fatigue by the same light for the same time brought mine nearly up to *b*. Fatigue by blue enabled her to trace green a good distance beyond F, but not quite so far as I could after the same fatigue. Her blue-violet junction was very indefinite, and the light was so bad that very little reliance could be placed on the readings obtained. Such as it was, the examination went to show that in her case the green sensation predominated over the rest, that the blue sensation came next, and that the red and violet were both so very much weaker as to produce very little impression, except when unmixed with other colours.

No. XVIII.—*Unusually Strong Blue.*

A Physiological Student.

He placed the junction of "red" with "green" at λ 6060, and that of "green" with "blue" at λ 5150. As this is usually found near the F line λ 4862, there was

evidently something abnormal. The junction of "blue" with "violet" he found at λ 4360—a quite normal position.

Fatigue by red for 30 seconds produced only a small effect, bringing the "green" to λ 6070, but after fatigue by green he found "blue" at λ 5330 and even at λ 5470—which is unusually far into the red side of the green.

After blue he found "violet" at λ 4440. He could see the H and K lines easily. Fatigue by violet did not cause the "blue" to reach beyond λ 4360, but this may have been the fault of the arc-lamp, which was burning badly and did not give much violet light. After fatigue by blue he missed the "green" altogether, stopping at about λ 5400 as the first change of colour, *i.e.*, well within the range of the red. But on making a second attempt he found "green" at λ 4810.

After fatigue by green he found "red" at λ 5390. He could see the red line of the potassium spectrum.

He must therefore possess the red and the violet sensations, with *either* a weak green or a strong blue. I incline to think the latter is the case, because he placed the red-green boundary where it would be for a green of quite normal strength, and the green-blue boundary after fatigue by blue, *when he found it*, was quite in the normal position, only it was *easily passed over*. This would indicate a strong blue rather than a weak green.

He was only partially colour-blind.

My thanks are due to Mr. R. W. DOYNE for some of these cases of colour-blindness, as well as for opportunities of seeing cases of abnormal vision not included in this paper; to Mr. W. W. FISHER for the continued loan of the large spectroscope from the Marlborough Collection; and to Professor GOTCH, in whose laboratory a great deal of the work was done, for the special opportunities he has given me of interesting his students in this subject and obtaining through them, not only instances of colour-blindness, but a very large number of examples of normal colour sensation.

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